Highlights from EF06 Topical Group

Huey-Wen Lin, Pavel Nadolsky, Christophe Royon

Weekly meetings in three topical tracks:

1. **Hadron structure and Parton Distribution Functions**
   - In-depth tests of QCD -- the unique QFT accessible in both perturbative and nonperturbative regimes
   - Essential input for EW precision and BSM studies in hadron scattering
   - 3-dimensional hadron structure, new PDF types (TMD's, GPD's, polarized, nuclear,…)

2. **QCD at small momentum fractions, saturation, diffraction**
   - Transition to the high-density regime of QCD
   - Increasingly relevant at the HL-LHC, FCC-hh, LHeC
   - Impact on the design of new detectors at FCC, etc.

3. **Nonperturbative models of hadrons and hadron spectroscopy**
   - PDFs on the lattice
   - New exotic hadronic states at the LHC, B-factories, …
     (overlaps with Rare Processes & Precision Measurements Frontier)
   - …

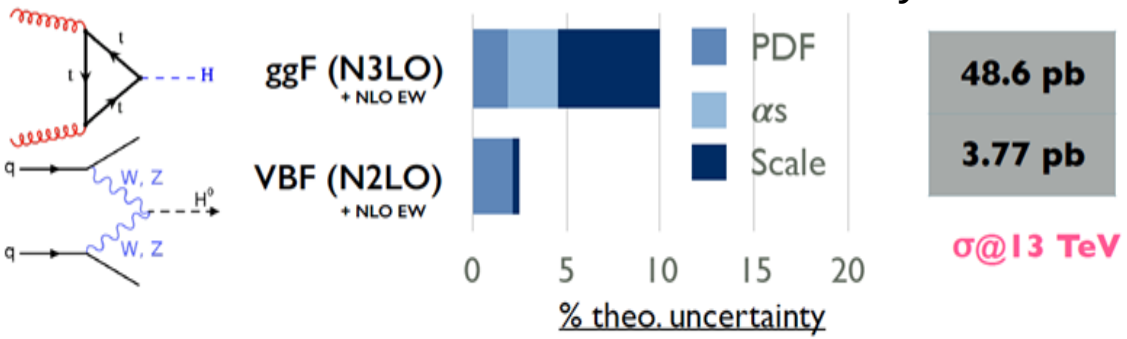
Agendas and slides from presentations at https://indico.fnal.gov/category/1140/

Overlapping topics with EF03, 04, 05, 07

PDFs and α_s introduce leading uncertainties in EW/BSM physics at hadron colliders

Talk by M. Ubiali

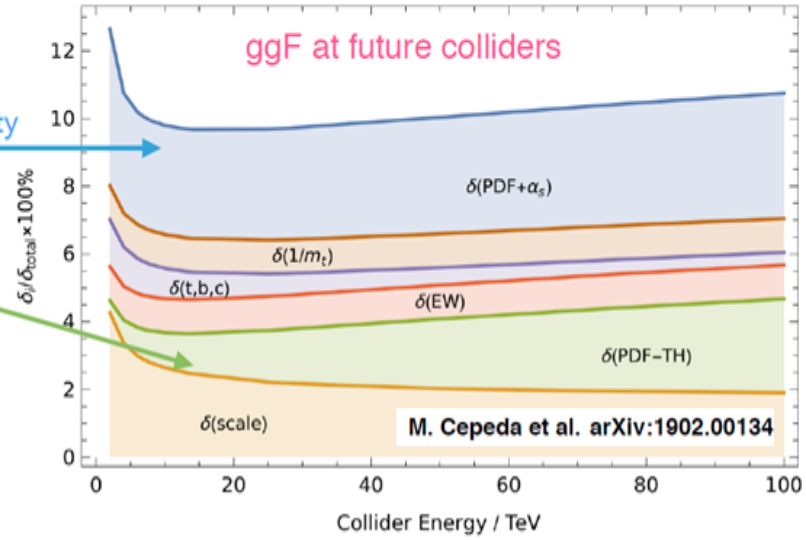
For example, in Higgs production at the HL-LHC and HE-LHC



PDF uncertainty significantly limits theory accuracy

PDF+as uncertainty

Th. mismatch



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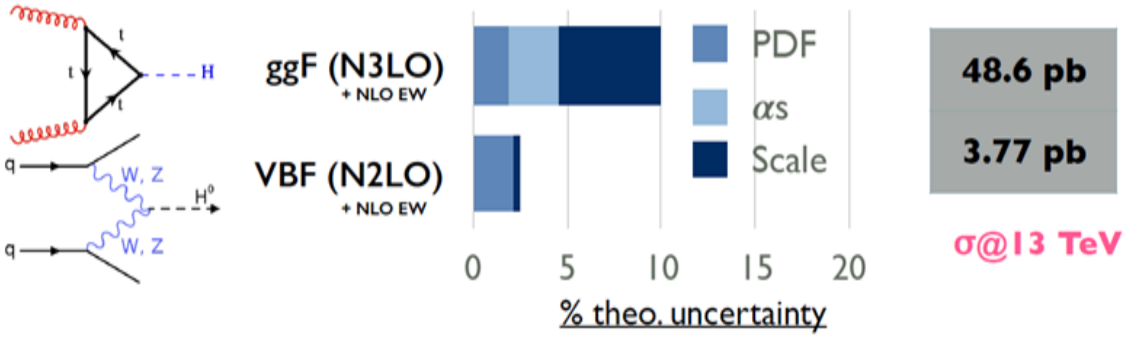
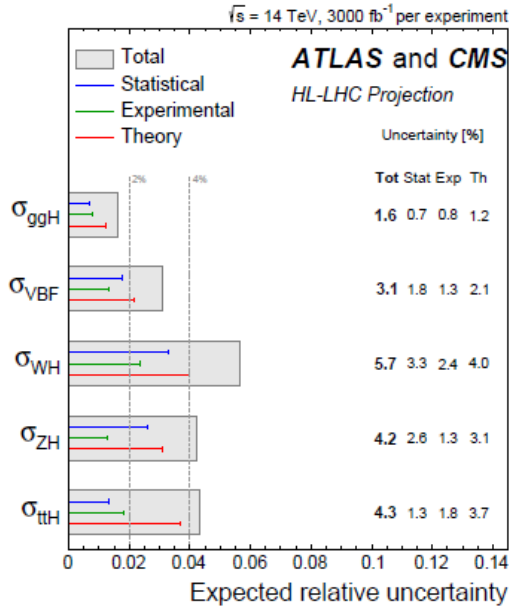


Reaching the targeted accuracy of PDFs at the HL-LHC/HE-LHC is not automatic:

which advancements in QCD theory & PDF determination will be required, as well as new measurements at the LHC and other facilities?



M. Cepeda et al., arXiv:1902.00134

New tasks for the PDF analysis in the HL-LHC era

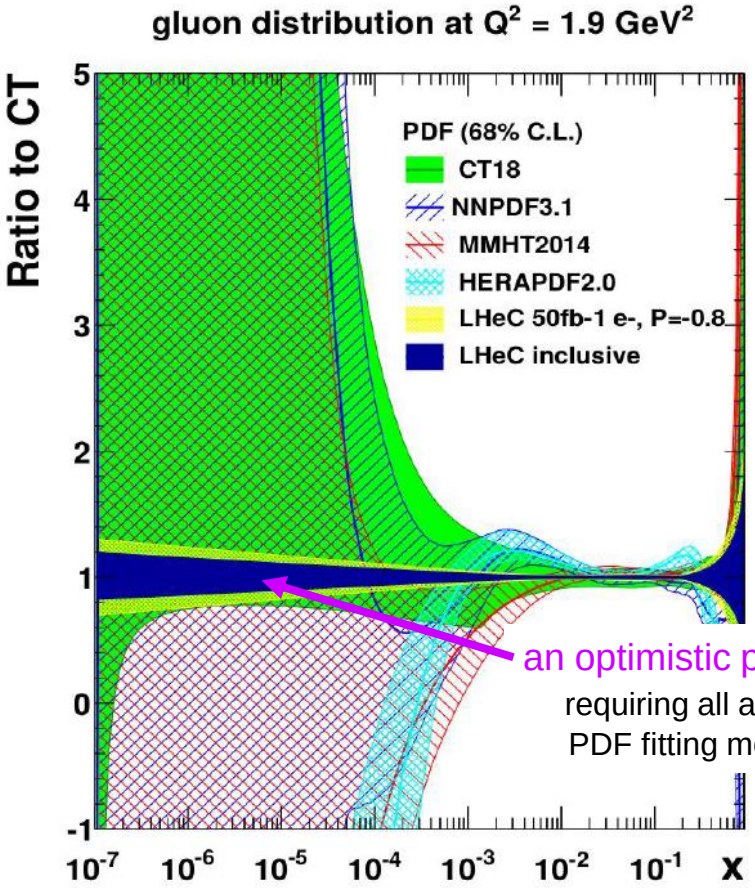
Obtain complete NNLO and N3LO predictions for PDF-sensitive processes	**Improve models for experimental correlated systematic errors**	**Find ways to constrain large-x PDFs without relying on nuclear targets**
Develop and benchmark fast NNLO interfaces	Estimate NNLO theory uncertainties	Develop an agreement on comparing and combining PDF fits

Talks by J. Huston, M. Guzzi, J. Rojo,M. Ubiali, P. Nadolsky, K. Xie

What can we learn about PDFs at future ep/eA colliders?

Talks by N. Armesto, T. Hobbs, F. Olness, A. Stasto

An ep collider operating concurrently with the HL-LHC can contribute critical **complementary** measurements of PDFs that are **independent** of the LHC systematic effects and free from high-mass BSM contributions



an optimistic post-LHeC uncertainty,
requiring all advancements in the PDF fitting methodology

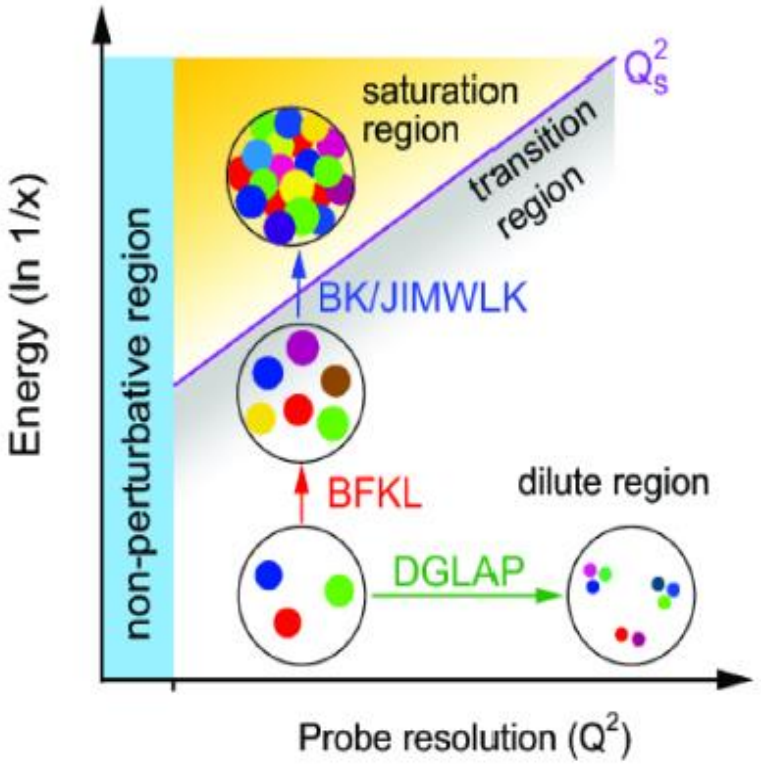
An **Electron-Ion Collider** can replace most of fixed-target and nuclear-target measurements constraining proton PDFs at large x. It will systematically study PDFs for heavy nuclei.

The **Large Hadron-Electron Collider** will supersede the HERA DIS measurements and extend the kinematic reach of DIS to very small x and large Q

EIC @ Snowmass: an EF06/07 meeting on the EIC physics potential for HEP, August 4

https://indico.fnal.gov/event/44510/

A new regime of QCD: low x, BFKL resummation, saturation



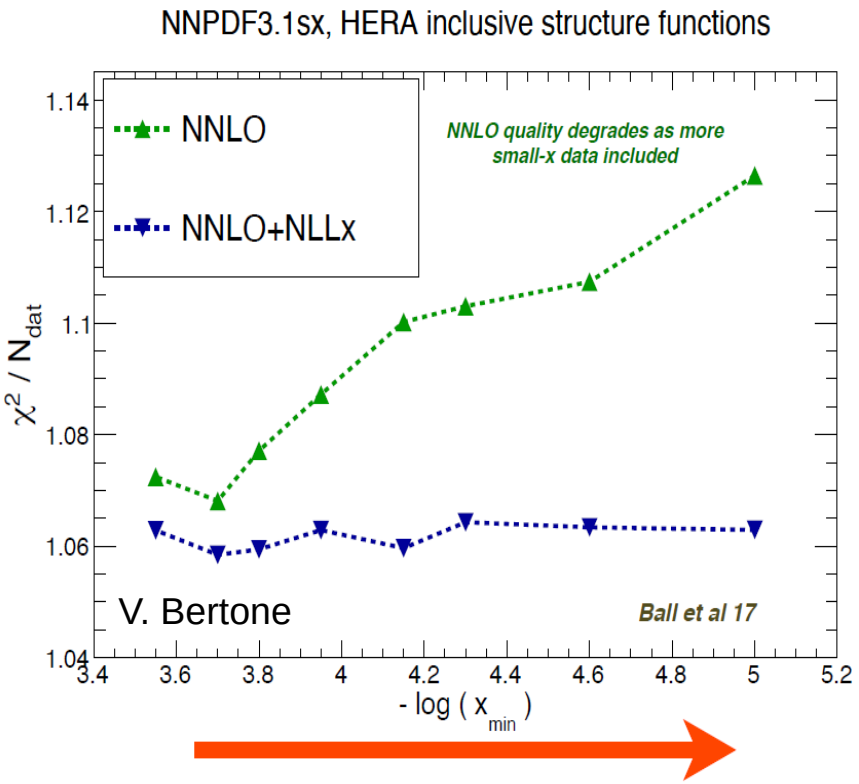
1. Which observables allow access to the high-parton-density regime of QCD at future facilities?

- Measurements of Mueller-Navelet jets (mini-jets), low-x heavy quark, hadron-hadron,Higgs-jet, trijet, vector meson production at LHC, LHeC, FCC-hh…; heavy ions (Kovchegov)

2. What is the realistic path toward a unified formalism describing transitions between DGLAP, BFKL, and saturation regimes?

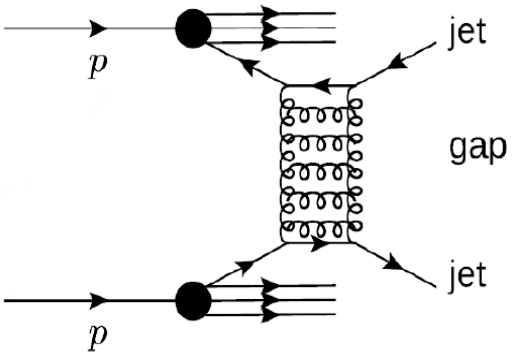
A new regime of QCD: low x, BFKL resummation, saturation

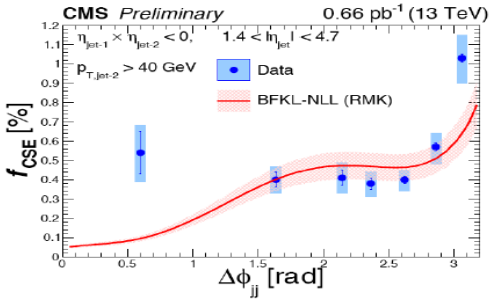
PDF fits based on **fixed order** (NNLO) and **small-*x* resumed** (NNLO+NLLx) theory



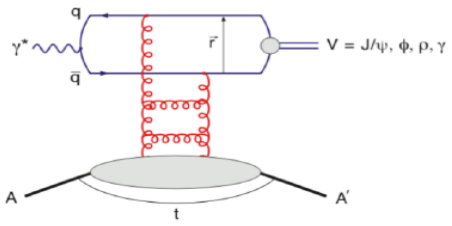
Resumation stabilizes fixed-order QCD at $x < 10^{-3}$; inclusive cross sections are not ideal for discrimination between DGLAP and BKFL scenarios

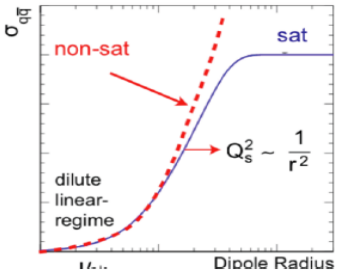
Dedicated observables to seek evidence of BFKL dynamics: Mueller-Tang production of hadronic jets with rapidity gap (Baldenegro), Mueller-Navelet jets (Sabio Vera), semi-hard processes (Celiberto), **…**

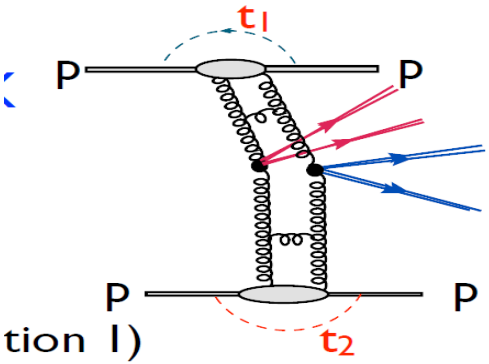


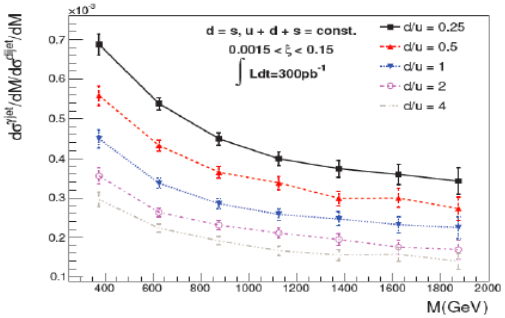


Hard or soft diffraction and saturation







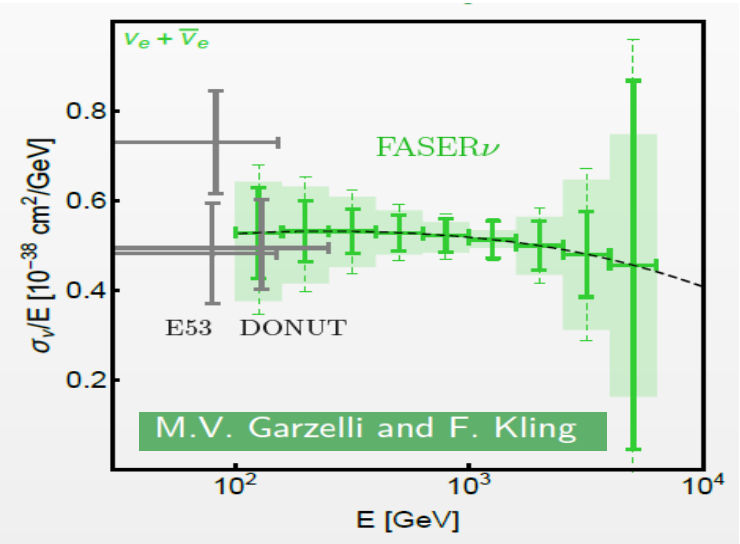


- Proton(s) intact after interaction and can be measured in roman pot detectors
- Better understanding of Pomeron structure in terms of quarks and gluons
- Many diffractive channels at the LHC/EIC

Barrera, Strikman, Takaki, ..

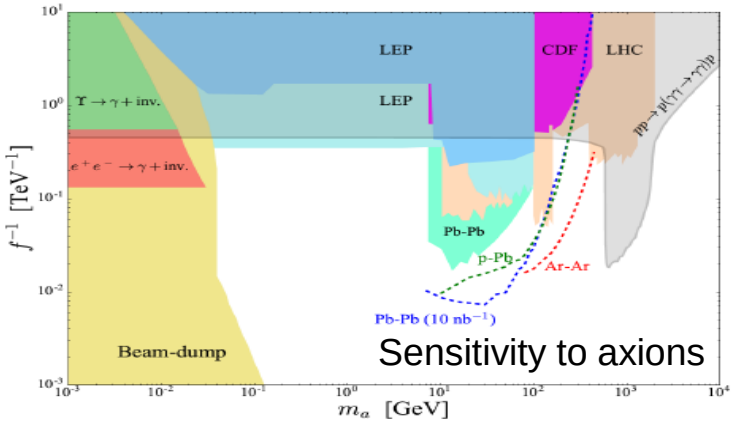
Forward detectors at high luminosity at the LHC

New forward detectors (FASER, FOCAL, particle spectrometers) can both test the less known aspects of QCD and search for BSM physics



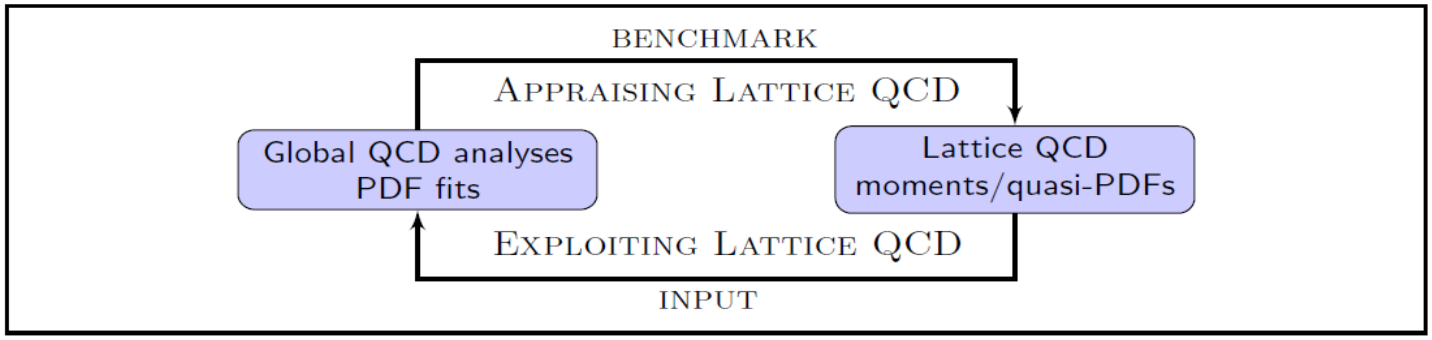
Averaged neutrino-nucleus DIS cross section in the FASER experiment

Forward detectors observing intact beam protons open new avenues for a variety of BSM searches (axions, dark sector,…)

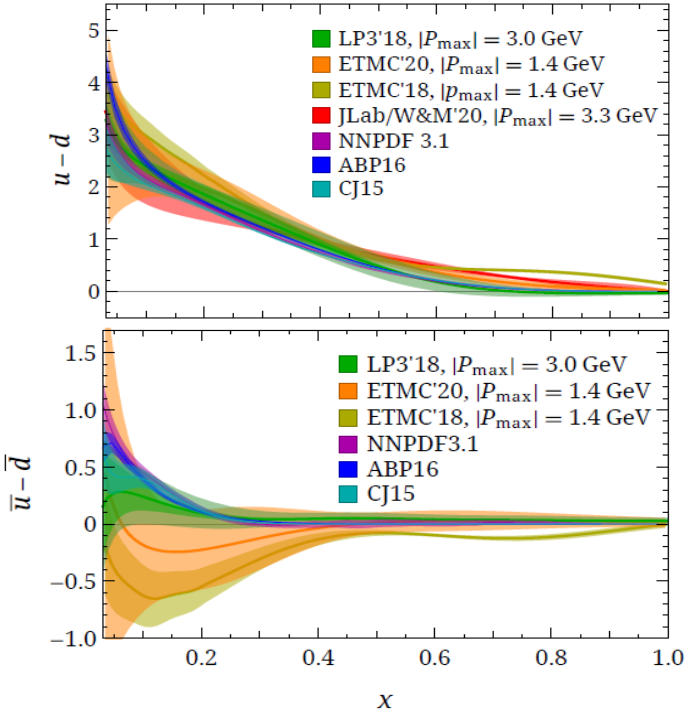


1. **What is required from forward detectors to enable decisive tests of QCD?**
2. **What is required from QCD modeling to enable decisive BSM searches?**

Lattice QCD: ab initio computations of PDFs



Talk by E. Nocera



Lattice QCD computes nonperturbative functions for the hadron structure (Mellin moments, quasi-PDFs, pseudo-PDFs) by discretizing the QCD Lagrangian density

This is a rapidly progressing field: computations of PDFs in several lQCD approaches have been compared against phenomenological PDF models at two workshops:

- PDFLattice2017, Oxford, March 2017
- PDFLattice2019, Michigan State University, Sept. 2019

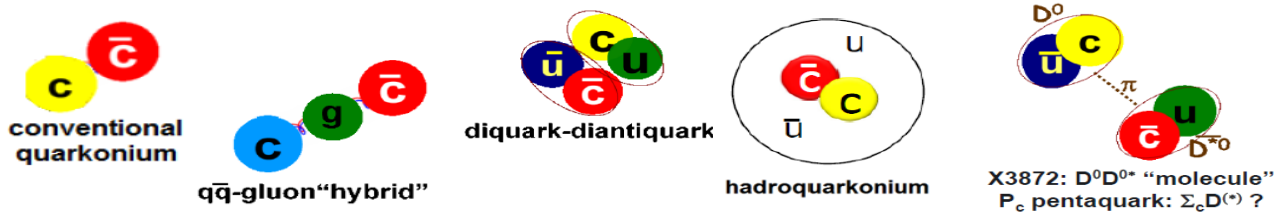
[Prog.Part.Nucl.Phys. 100 (2018) 107; arXiv:2006.08636]

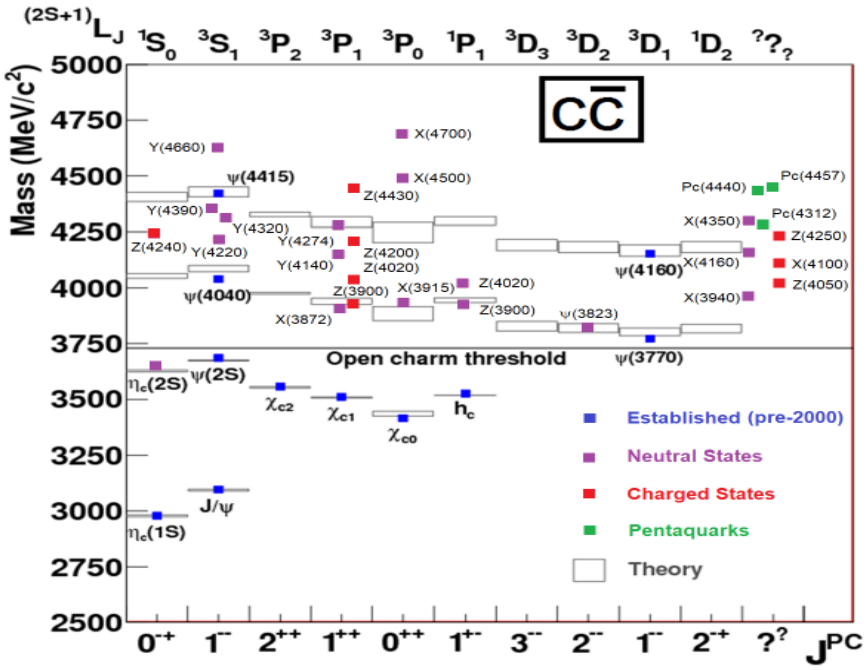
Pheno PDFs provide empirical benchmarks for lattice QCD computations. Lattice QCD has the potential to predict PDF combinations not accessible in the experiment.

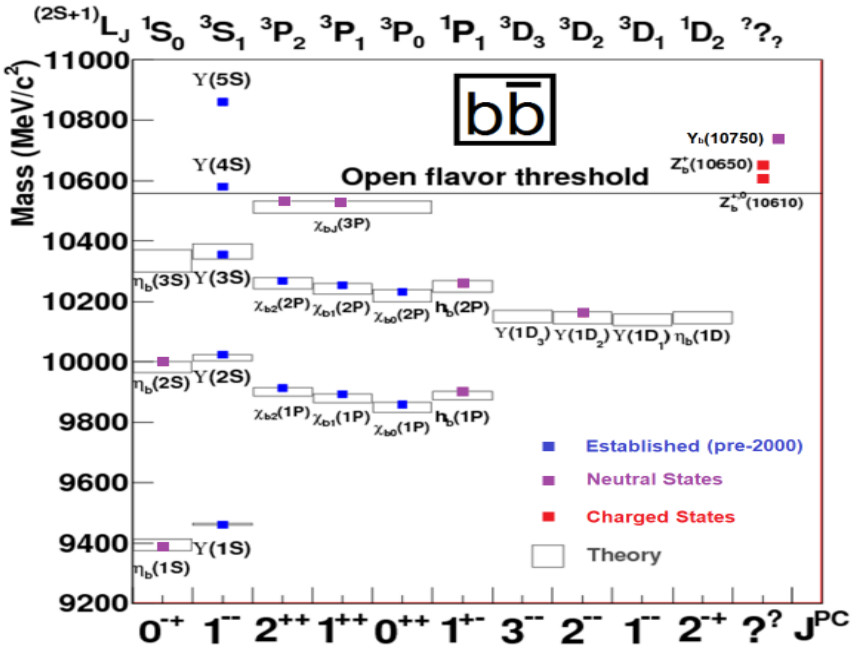
Heavy flavor tetra- and pentaquarks

It is becoming increasingly clear that no single theoretical paradigm explains all > 40 heavy-quark exotics

EF06 talks by B. Fulsom, R. Lebed, R. Mitchell, A. Pompili, T. Skwarnicki, J. Stevens







Hadron Spectroscopy / Bryan FULSOM (PNNL) / Snowmass Preparatory Joint Session / 2020.07.08

EF06 Focus Questions

1. What is the best approach to reduce systematic uncertainties in LHC measurements to achieve the accuracy of PDFs envisioned by electroweak precision studies at the high-luminosity LHC?
2. **What is the feasible strategy for obtaining accurate PDFs for N3LO QCD computations? Which theoretical advances and computational tools will be necessary?**
3. **What is the potential of new deep inelastic scattering facilities (EIC and LHeC) for probing the hadronic and nuclear structure in the regions relevant for HEP experiments?** How can the experience of the HEP community be transferred to enhance the potential of the EIC and LHeC studies?
4. How does the knowledge of hadron structure affect measurements of the QCD coupling constant in various processes?
5. When do power-suppressed contributions to the hadron structure become important in NXLO QCD calculations? What are the best approaches to predict or measure them?
6. **What are the best observables to look for low-x resummation effects predicted by the Balitsky-Fadin-Kuraev-Lipatov resummations?** Define less inclusive variables compared to pure Mueller-Navelet jets, and compute predictions on jet gap jet observables at NLO.
7. **What are the prospects of running forward proton detectors at the LHC at high luminosity?** What will be their sensitivity to anomalous couplings between photon, W, Z bosons, top quarks…
8. **How to observe saturation effects or high-gluon density regimes at the LHC and the EIC?**
9. Which diffractive measurements can be performed at the LHC and the EIC in order to understand better the structure of the Pomeron?
10. Which detectors (including acceptance/resolution) will be needed at the LHC and the EIC in order to perform the best possible measurements of energy, particle production in the very forward region?
11. **How can the LHC, LHeC, and FCC improve our knowledge of the 3-dimensional structure of nucleons and nuclei?**
12. **How do excited hadronic states with two or more heavy quarks form and decay?**
13. What are the BSM connections for hadron spectroscopy at future facilities?
14. How will artificial intelligence methods advance extraction of nonperturbative hadronic functions from experimental measurements?